UDC 551.557:551.42.1(789)

Geostrophic Wind Deviation in the Upper Troposphere and Lower Stratosphere in the El Paso–White Sands Area

HSING-WU WU and KENNETH H. JEHN—*The University of Texas, Austin, Tex.*

ABSTRACT—Wind data at and above the 500-mb level taken from the El Paso, Tex., rawinsonde Station (rawin) and pressure-height data at the same levels from Albuquerque, N. Mex., Midland, Tex., Tucson, Ariz., and Chihuahua, Mexico, during the 1965–66 winter and the 1966 summer periods were used to study geostrophic wind deviation. Geostrophic winds were computed directly from the pressure-height data by a finite-difference method and compared to the actual wind as measured at El Paso. The variations of the "apparent" geostrophic wind deviation with wind speed and pressure-height were examined. Errors involved were analyzed and the "true" geostrophic wind deviation and the total wind accelerations were estimated. Results of the study reveal: (1) that despite the improvement in the accuracies of the radiosonde pressure-height and rawin data, the errors in the data still account for a large portion of the apparent geostrophic wind deviation at higher levels (at and above the 150-mb level); (2) that to use the geostrophic wind approximation in cases with wind speed less than 20 m/s would probably result in vector wind errors of the order of 40 percent or more; and (3) that the mean true geostrophic wind deviation increases when the mean actual wind speed increases, and the estimated mean total wind accelerations range from 1×10^{-4} to 5×10^{-4} $m \cdot s^{-2}$ at and above the 500-mb level.

1. INTRODUCTION

It is well realized by meteorologists that wind determinations from pressure analyses often give a poor approximation to the actual wind. Nevertheless, this technique has often been employed to approximate the actual wind in many problems. Although there have been many attempts to evaluate geostrophic and or gradient wind deviations and to investigate their occurrence in the free atmosphere, the poor quality of radiosonde pressure-height data at levels above 300 mb has severely restricted studies of geostrophic deviations to the troposphere. Over the past 15 yr, however, radiosonde accuracies have improved (Lenhard 1970); therefore, it is feasible to extend this kind of study into higher levels, where geostrophic deviations have not yet been studied intensively. Thus, the main purpose of this study is to extend previous studies of the geostrophic deviations from the middle troposphere to the lower stratosphere and to study the variations of these deviations with height and wind speed. Also included in the study is an analysis of the errors and estimates of the "true" geostrophic deviation and total wind acceleration in the study area.

The methods used in previous studies of geostrophic deviation can be broadly classified into methods A, B, and C, according to the nature of the data used in determining the deviations. Method A uses wind data obtained by conventional upper wind observations [radio direction-finding (rawin) or theodolite (pibal) observations] as actual wind to compare with geostrophic or gradient winds determined from an isobaric contour chart. This method was employed by Houghton and Austin (1946), Neiburger et al. (1948), Bannon (1949), Murray and Daniels (1953), Murray (1954), Kochanski (1958), and Zobel (1958).

Wind data collected by research aircraft or rocketsonde are used as actual wind in method B. The geostrophic or gradient winds are determined from height gradients on contour charts as in method A. Wind measurements made by aircraft of Project Jet Stream were used by Endlich and McLean (1960) in a study of the geostrophic and gradient wind deviations in jet streams. Kays (1966) compared rocketsonde winds and geostrophic winds determined from Scherhag's 10-mb maps and obtained some statistics concerning geostrophic deviation in the higher atmosphere.

Method C differs from methods A and B in that geostrophic deviations are determined from accelerations without recourse to pressure-height data. The accelerations are determined either from constant-pressure balloon trajectory data as has been done by Neiburger and Angell (1956) and Giles and Peterson (1957), or by evaluating local time-and space variations of wind speed and direction, using observed wind data (Godson 1950). It also includes a technique by which geostrophic winds are computed from observed winds using the balance equation (Endlich 1968).

The method employed in the study being reported here represents an alternative technique by which geostrophic winds are computed directly from pressure-height data by a finite-difference method. Five radiosonde stations—El Paso and Midland, Tex., Tucson, Ariz., Chihuahua, Mexico, and Albuquerque, N. Mex., surrounding the White Sands, N. Mex., Missile Range area—were found to constitute a synoptic scale grid suitable for employing a finite-difference method in computing geostrophic winds directly from pressure-height observations. The locations of the stations are shown in figure 1.

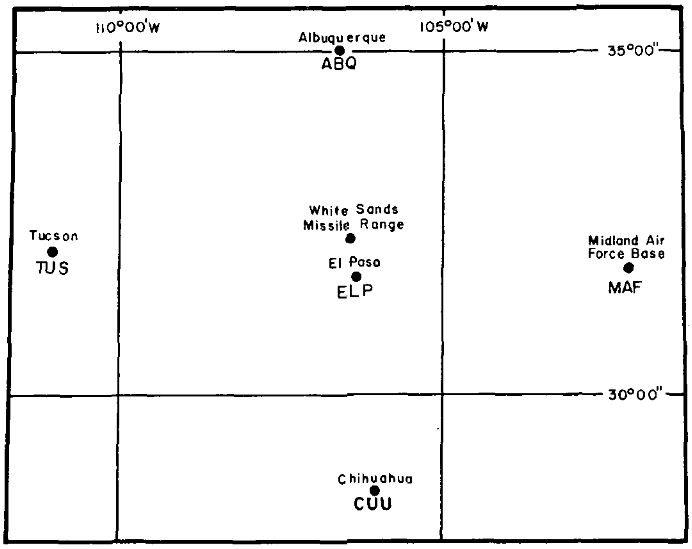

FIGURE 1.—Radiosonde station locations.

The fact that radiosonde stations at Albuquerque, El Paso, and Chihuahua are situated in an approximate north–south line, and Tucson, El Paso, and Midland in an east–west direction makes this grid especially suitable. With El Paso approximately at the center of the grid, the computation of geostrophic deviations becomes a straightforward matter. Geostrophic winds were computed using pressure-height observations from the four stations around El Paso; wind observations obtained at El Paso were used to represent the actual wind in the area.

There are several reasons for employing this technique. One obvious reason is that there is then no need to construct isobaric contour charts and measure height gradients. This enables us to reduce greatly the amount of labor involved and to handle a larger data sample. The measurement of geostrophic wind on an isobaric contour chart includes errors arising from individual variation in map construction and contour gradient measurement. These errors have been shown (e.g. by Neiburger et al. (1948), Murray 1954) to account for a large portion of the overall errors in the determination of geostrophic deviation using methods A or B. Being able to avoid them is another advantage of the technique used in this study.

2. DATA AND PROCEDURE

Pressure-height observations at Tucson (TUS), Midland (MAF), Albuquerque (ABQ), and Chihuahua (CUU), and wind observations at El Paso (ELP) for one winter period (December 1965 through February 1966) and one summer period (June through August 1966) were collected for this study. The data consist of twice-daily observations; 0000 and 1200 GMT (2300 and 1100 GMT for Chihuahua) from all levels at and above the 500-mb level. The pressure-height data are given to the nearest 10 geopotential meters and observed wind data to the nearest 10° in direction and 1 kt in speed. Only those cases with all four height observations (from TUS, MAF, ABQ, and CUU) and one wind observation (from ELP) available were selected for this study. In all, 1,630 such cases were obtained. Of these, 816 cases were from the winter period and 814 cases were from the summer period. The numbers of cases for individual isobaric levels vary from approximately 100 at levels below 200 mb to as small as 10 at the 20-mb level. No simultaneous sets of pressure-height and wind data were available at the 10-, 7-, and 5-mb evels for these periods.

The x- and y- components of geostrophic wind, u_g and v_g, were computed by a finite-difference method:

$$u_g=-\frac{g}{f}\frac{z[\text{ABQ}]-z[\text{CUU}]}{L[\text{ABQ}-\text{CUU}]}$$

and

$$v_g=+\frac{g}{f}\frac{z[\text{MAF}]-z[\text{TUS}]}{L[\text{MAF}-\text{TUS}]}$$

where z is the pressure-height at the specified station, L[ABQ−CUU] and L[MAF−TUS] are distances between the two stations specified in the brackets, g is the gravitational acceleration, and f is the Coriolis parameter. The numerical values used for the constants are $L[\text{ABQ}-\text{CUU}]=7.15\times10^5$ m, $L[\text{MAF}-\text{TUS}]=8.26\times10^5$ m, $g=9.73$ m $\cdot$ s^{-2}, and $f=7.29\times10^{-5}$ s^{-1}. Here, g is taken to be the standard value for 20 km above sea level at 30° latitude and f is the Coriolis parameter at 30° latitude.

The geostrophic wind deviation is expressed in terms of:

1. Absolute geostrophic speed deviation, $|V_{ag}|$,

$$|V_{ag}|=|V_a-V_g|;$$

2. Absolute geostrophic vector wind deviation, $|\mathbf{V}_{ag}|$,

$$|\mathbf{V}_{ag}|=|\mathbf{V}_a-\mathbf{V}_g|=[(u_a-u_g)^2+(v_a-v_g)^2]^{1/2};$$

3. Absolute geostrophic direction deviation, $|D_{ag}|$,

$|D_{ag}|$ is the absolute value of the difference in actual wind and geostrophic wind direction $(0\leq|D_{ag}|\leq180°)$;

4. Relative geostrophic speed deviation, R_s,

$$R_s=|V_{ag}|/V_a=|V_a-V_g|/V_a$$

calculated only for cases with $V_a>2.5$ m/s;

5. Relative geostrophic vector wind deviation, R_v,

$$R_v=|\mathbf{V}_{ag}|/V_a=|\mathbf{V}_a-\mathbf{V}_g|/V_a$$

calculated only for cases with $V_a>2.5$ m/s;

6. Root-mean-square geostrophic vector wind deviation, rms (v),

$$\text{rms }(v)=\left(\sum_N|\mathbf{V}_a-\mathbf{V}_g|^2/N\right)^{1/2};$$

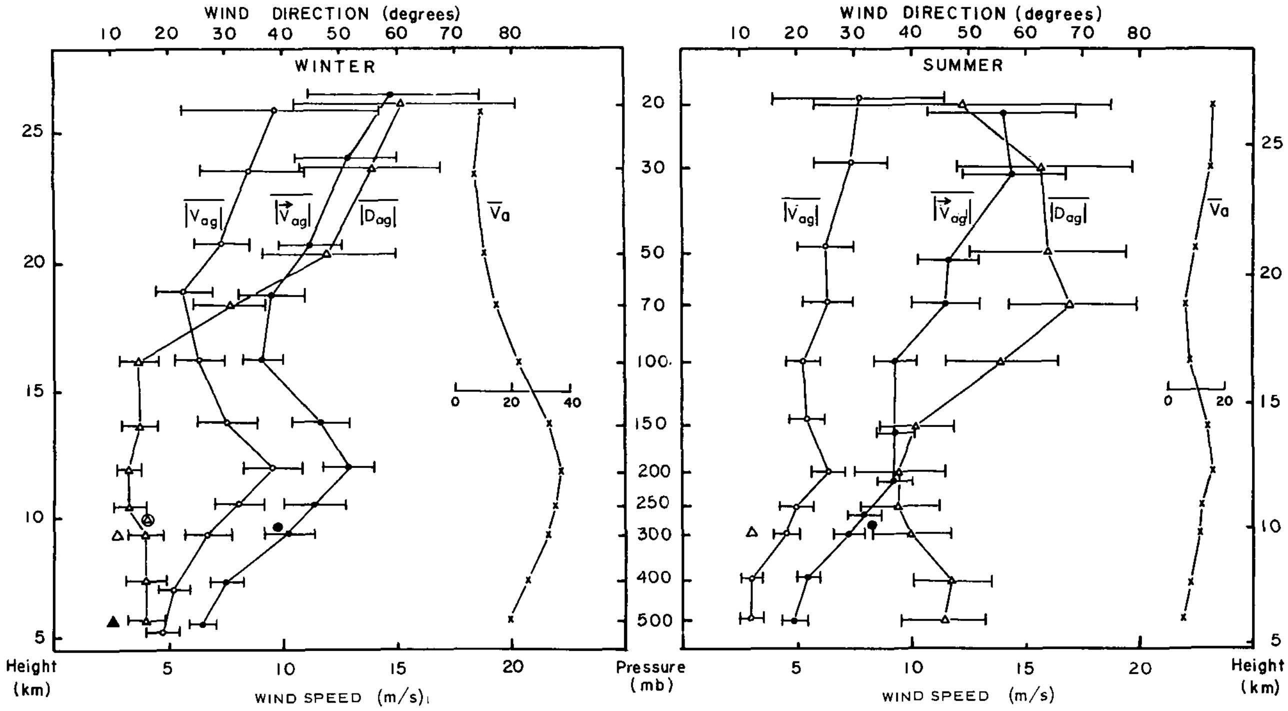

FIGURE 2.—Mean actual wind speed, $\overline{V_a}$, and mean absolute geostrophic deviations in speed, $\overline{|V_{ag}|}$; vector wind, $\overline{|\mathbf{V}_{ag}|}$; and direction, $\overline{|D_{ag}|}$. Horizontal line segments represent 90-percent confidence limits for the means. Values of $\overline{|D_{ag}|}$ obtained by Bannon (1949) and Neiburger and Angell (1956) are shown by symbols ▲ and △, respectively. Values of $\overline{|\mathbf{V}_{ag}|}$ obtained by Giles and Peterson (1957) and Neiburger and Angell (1956) are represented by symbols Ⓐ and ●, respectively.

7. Root-mean-square geostrophic speed deviation, rms (s),

$$\text{rms }(s)=\left(\sum_N (V_a-V_g)^2/N\right)^{1/2}; \text{ and}$$

8. Root-mean-square geostrophic direction deviation, rms (D),

$$\text{rms }(D)=\left(\sum_N (|D_{ag}|)^2/N\right)^{1/2};$$

where

u_a is the actual wind speed in east–west direction (west wind positive),

v_a is the actual wind speed in north–south direction (south wind positive),

V_a is the actual wind speed $=(u_a^2+v_a^2)^{1/2}$,

V_g is the geostrophic wind speed $=(u_g^2+v_g^2)^{1/2}$,

$\mathbf{V}_a$ is the actual wind vector,

$\mathbf{V}_g$ is the geostrophic wind vector, and

N is the sample size.

All the deviation parameters computed according to the above definitions are termed "apparent" geostrophic deviations. To avoid needless repetition, the adjective "geostrophic" will be dropped in the remainder of this article when referring to geostrophic deviation.

3. APPARENT GEOSTROPHIC DEVIATION

The apparent deviation computed according to the definitions given in section 2 represents the combined effect of an unknown true deviation and the errors involved in the computation of this deviation. No attempt was made to correct the errors caused by the slight deviation of the positions of the radiosonde stations from north–south and east–west direction (see fig. 1) and the 1-hr observation time difference between Chihuahua and the other four stations. It is obvious that the individual values computed would not be reliable due to the random errors involved in the computation, but reliable estimates of the deviation could be obtained by computing mean deviations. Hence, mean values were computed separately for the summer period and the winter period.

The general climatology in the study periods can be briefly described as follows. In the winter period (December 1965 through February 1966), the westerlies prevail throughout the entire layer with maximum wind (37.7 m/s) occurring at the 200-mb level; in the summer period (June through August 1966), a transition layer at about the 100-mb level divides the westerlies below from the easterlies above this level. The maximum westerly wind of 16.2 m/s occurs at the 200-mb level, and the maximum easterly wind of 17.0 m/s at or above the 20-mb level.

The mean actual wind speed and three mean absolute deviation parameters—$\overline{|V_{ag}|}$, $\overline{|\mathbf{V}_{ag}|}$ and $\overline{|D_{ag}|}$ are shown in figure 2 together with 90-percent confidence intervals for each mean. Three root-mean-square deviation parameters—rms (v), rms (s), and rms (D) are similarly shown in figure 3. Also shown in figures 2 and 3 are some of the results of earlier studies of geostrophic wind deviation.

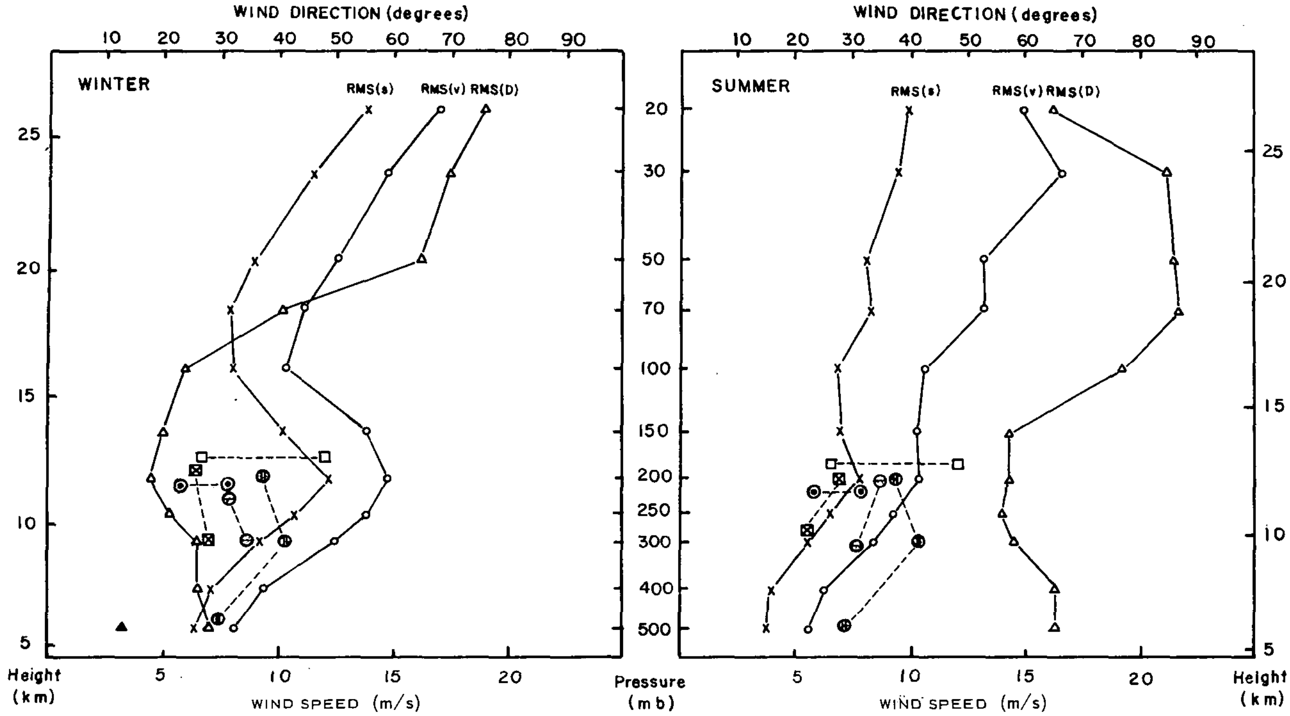

FIGURE 3.—Root-mean-square geostrophic deviations in speed, rms (s), vector wind, rms (v), and direction, rms (D). Values of rms (v) obtained by Murray [1954] (◎), Zobel [1958] (⊙), and Kochanski [1958] (⊖); values of rms (s) obtained by Kochanski [1958] (⊠) and Endlich and McLean [1960] (□); and the value of rms (D) obtained by Bannon [1949] (▲) are also shown in the figure.

In figure 2 for the levels below 100 mb, the mean absolute direction deviation, $\overline{|D_{ag}|}$, shows only slight variation with height. On the average, $\overline{|D_{ag}|}$ has values of the order of 15° for winter whereas summer values are some 30° larger than winter values. This difference probably occurs because weak winds prevail in the summer period, while strong winds, which are found to be associated with smaller deviation angles, occur much more frequently in winter. The sudden increase of $\overline{|D_{ag}|}$ above the 100-mb level in winter and above the 150-mb level in summer must be attributed partly to the rather weak mean wind speed and partly to the decline in quality and quantity of pressure-height data at these levels.

Mean absolute speed deviation, $\overline{|V_{ag}|}$, and mean absolute vector wind deviation, $\overline{|\mathbf{V}_{ag}|}$, can be seen to vary systematically with mean actual wind speed below the 100-mb level. Above the 100-mb level, this systematic variation begins to disappear, presumably due to the masking effect of the errors. The mean absolute vector wind deviation is, of course, larger than the mean absolute speed deviation. The difference between these two quantities is smaller at lower levels than at higher levels. On the average for both summer and winter, this difference is about 1.8 m/s at the 500-mb level, about 4 m/s at the 150-mb level, and about 7 m/s at the 20-mb level.

Previous studies yielded, for 10,000 ft., a mean value of absolute speed deviation of the order of 3.6 m/s (Godson 1950) and a mean value of absolute vector wind deviation of 4.8 m/s (Houghton and Austin 1946). Godson's study also gave an average value of 15° for the mean absolute direction deviation. The study by Kays (1966) gave a value of 5.9 m/s for the mean absolute speed deviation and a value of 8.1 m/s for the mean absolute vector wind deviation at the 10-mb level. The results of previous studies discussed below are also plotted in figure 2.

Bannon (1949) found that the mean absolute direction deviation was of the order of 10° at the 500-mb level. However, Bannon's results are probably biased since low wind velocities (less than 18 kt) were excluded from his study. The absolute deviation angle calculated from constant-pressure balloon observation data at the 300-mb level was found to be 12° by Neiburger and Angell (1956). Compared with the results of the present study, the mean absolute vector wind deviation at 200- and 300-mb levels (3.8 m/s) obtained by Giles and Peterson (1957) is rather small; but the mean actual wind speed for their data is only about two-thirds of the mean actual wind speed for the data used in this study. A value of 9.8 m/s for the mean absolute vector wind deviation was found at the 300-mb level by Neiburger and Angell (1956).

In figure 3, all three rms values show patterns similar to those shown in figure 2. Also plotted in figure 3 are the apparent rms vector wind deviation, rms (v), obtained by Murray (1954), by Zobel (1958), and by Kochanski (1958). Murray's values were computed for the transition month of April 1950; therefore, they are plotted on both the left hand (for winter) and the right hand (for summer) part of figure 3. Zobel's values were obtained from one year of data (December 1954 through November 1955) and so are also plotted on both parts of figure 3. Kochanski divided his data into winter and summer; his results are plotted accordingly. The value of rms direction deviation, rms (D), obtained by Bannon (1949) and the values of rms speed deviation, rms (s), obtained by Kochanski (1958) and by Endlich and McLean (1960) are also shown in the figure. Since the nature of the data, the analysis area, period, and technique used are different for the various studies, strict comparisons of the results are not possible; however, the results agree reasonably well, in the order of magnitude sense, with the results obtained from this study.

To study the variations of geostrophic deviation with wind speed, three deviation parameters—relative speed deviation, R_s, absolute direction deviation, $|D_{ag}|$, and relative vector wind deviation, R_v,—were further subdivided and averaged with respect to different ranges of actual and geostrophic wind speed; and for easier interpretation of the variations with respect to wind speed and height, those average values with sample size greater than 10 were plotted on separate figures and isopleths were drawn. Only one of the figures, the one for $\overline{R}_v$ with respect to actual wind speed ranges (fig. 4), is presented in this paper and will be discussed later. First, however, we will discuss briefly the variations of $\overline{|D_{ag}|}$ and $\overline{R}_s$ using the figures not included in this paper.

Generally speaking, in winter the mean absolute direction deviation decreases from more than 30° for actual wind speeds less than 10 m/s to less than 10° for actual wind speeds of the order of 40 m/s. A slight increase of $\overline{|D_{ag}|}$ occurs in the layer between the 150- and 100-mb level for actual wind speed greater than 45 m/s. A similar pattern is observed in the variations of $\overline{|D_{ag}|}$ with geostrophic wind speed. Large deviation angles appear with lower actual and geostrophic wind speed as expected. Results from a study of geostrophic deviation at 10,000 ft by Godson (1950) revealed that large deviation angles were associated with low geostrophic wind speeds. One of the conclusions from Neiburger and Angell's (1956) study is that (at the 300-mb level) the average angle between actual and geostrophic wind varies inversely with actual wind speed. In summer, $\overline{|D_{ag}|}$ decreases with both increasing actual and geostrophic wind speed, and large values of $\overline{|D_{ag}|}$ occur at higher levels and with lower wind speeds. Theoretically, the angle between geostrophic wind and actual wind direction is inversely proportional to geostrophic wind speed [see Godson (1950) for the discussion of this relation]. The results obtained in this study verify this theoretical prediction for geostrophic wind speeds less than 40 m/s.

The variations of mean relative speed deviation, $\overline{R}_s$, with actual wind and geostrophic wind speed are here briefly described. Below the 100-mb level in winter, $\overline{R}_s$ decreases with actual wind speed, with values less than 25 percent occurring for wind speed ranges from about 25 to 45 m/s. A slight increase of $\overline{R}_s$ appears at middle levels (250 to 150 mb) for actual wind speed greater than

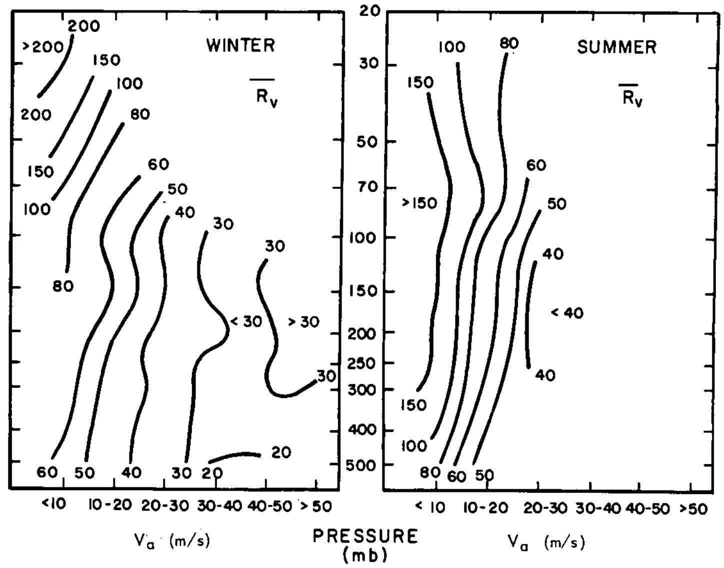

FIGURE 4.—Distributions of mean relative geostrophic vector deviation, $\overline{R}_v$ (percent), with respect to actual wind speed, V_a.

50 m/s. With respect to geostrophic wind speed, the variations are less systematic but, in general, they still show a tendency of a decrease and then a slight increase as geostrophic wind speed increases. $\overline{R}_s$ tends to increase quite rapidly with height above the 100-mb level, probably due mainly to the decreasing quality of pressure-height and wind observations at higher levels. In summer, the decrease of $\overline{R}_s$ with increase of actual wind speed is quite clearly shown in the results. The magnitude of $\overline{R}_s$ is, on the average, 10 percent higher than the corresponding values for winter. The variations with respect to geostrophic wind indicate a slightly different pattern. The results show maximum values of $\overline{R}_s$ in regions corresponding to geostrophic wind speeds of 10–20 m/s, but for geostrophic wind speed greater than 20 m/s $\overline{R}_s$ again decreases with increasing wind speed.

Figure 4 shows the variations of relative vector wind deviation, $\overline{R}_v$, with mean actual wind speed. We see that in winter $\overline{R}_v$ decreases with increasing actual wind speed except at levels between 300 and 150 mb where it shows a slight increase for actual wind speed greater than 50 m/s. Below the 100-mb level, the variation of $\overline{R}_v$ with height is relatively small. The extremely large values at higher levels corresponding to lower wind speeds resulted mainly from relatively large errors in pressure-height and rawin data (see sec. 4). In summer, $\overline{R}_v$ decreases with increasing actual wind speed. It also shows a small variation with height. The tendency of $\overline{R}_v$ to increase with height in both winter and summer is an expected feature, since the quality of data declines at higher levels.

From the results discussed above, we find that the values of $\overline{R}_s$ and $\overline{R}_v$ corresponding to lower wind speeds (which generally means that the study area is situated in regions of weak contour gradient; i.e., col, High, or Low), are usually large and tend to bias the average values

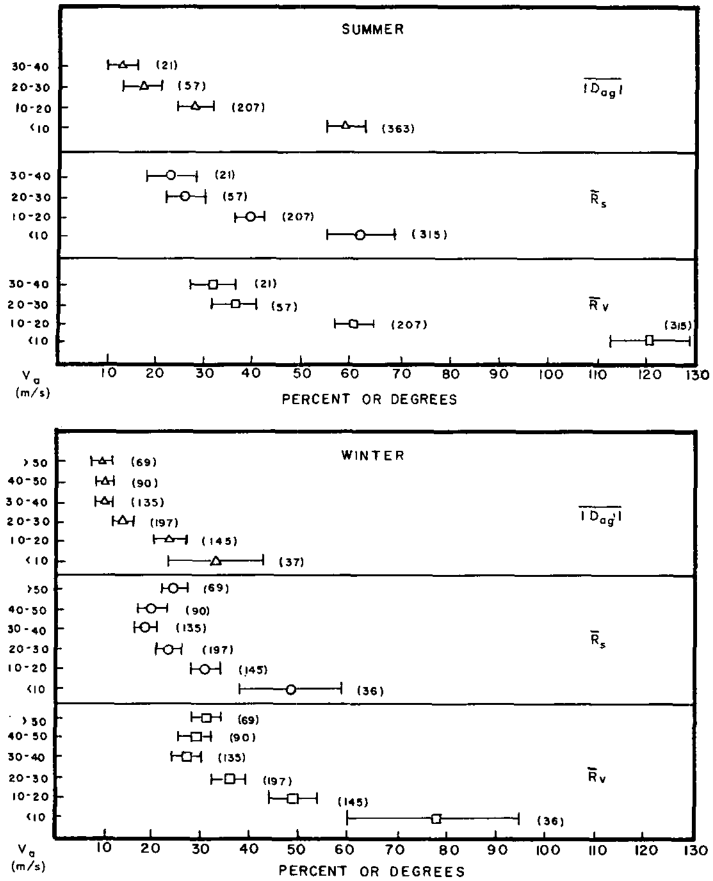

FIGURE 5.—Mean relative geostrophic vector deviation, $\overline{R}_v$ (percent); mean relative geostrophic speed deviation, $\overline{R}_s$ (percent); and mean absolute geostrophic direction deviation, $\overline{|D_{ag}|}$ (deg.), as a function of actual wind speed, V_a, for the layer between 500 and 100 mb. Numerical values in parentheses are the number of cases.

of the relative speed or vector deviations and the direction deviations. The grand mean might overestimate these deviations due to this bias. Therefore, mean values corresponding to those data with wind speed greater than 10 and 20 m/s were also computed. [The complete set of these mean values can be found in the report by Wu (1970).] As expected, exclusion of low wind speeds from the data sample resulted in reducing average values of $\overline{R}_s$, $\overline{|D_{ag}|}$, and $\overline{R}_v$, especially in the summer months. The mean relative speed deviation at 10,000 ft (about 700 mb) obtained by Godson (1950) was just under 30 percent, which is close to the value of 28 percent for the 500-mb level in winter obtained in this study (Godson's data were taken from the month of November).

Using constant-pressure balloon trajectory data at the 300-mb level (taken from the months of April, May, and June), Neiburger and Angell (1956) obtained a value of 39 percent for relative speed deviation. In this study, the values were found to be 23 percent for winter and 48 percent for summer (average value of these two is about 38 percent). Kays' (1966) comparison of geostrophic wind and actual wind observed by rocketsonde at the 10-mb level gave an average value of 39 percent for relative vector wind deviation and an average value of 29 percent for relative speed deviation.

Below the 100-mb level for a particular mean actual wind speed range, the variations with height of the mean absolute direction deviation, $\overline{|D_{ag}|}$, the mean relative speed deviation, $\overline{R}_s$, and the mean relative vector deviation, $\overline{R}_v$, were found to be relatively small in both winter and summer. Therefore, single mean values for the lowest seven levels (500 mb—100 mb), for each of the parameters $\overline{|D_{ag}|}$, $\overline{R}_s$, and $\overline{R}_v$ were computed. These mean values, plotted in figure 5 with 90-percent confidence intervals, should represent the mean values that one would expect to find in the higher troposphere and lower stratosphere. This figure shows that in winter the mean relative vector wind deviation, $\overline{R}_v$, and the mean relative speed deviation, $\overline{R}_s$, decrease with increasing actual wind speed when actual wind speed is less than 40 m/s. The two deviations exhibit a slight tendency to increase when the actual wind speed is greater than 40 m/s, although this increase is not large enough to be considered significant.

The mean absolute direction deviation, $\overline{|D_{ag}|}$, also shows the same variation with actual wind speed, except that when the actual wind speed is greater than 40 m/s $\overline{|D_{ag}|}$ does not increase with wind speed; instead, an almost constant value of 10° is found.

The minimum values occur in the actual wind speed range of 30–40 m/s for both mean relative vector wind deviation (minimum value of the order of 27 percent) and mean relative speed deviation (minimum value of the order of 19 percent). The minimum value for mean absolute direction deviation (about 10°) occurs when the actual wind speed is greater than 30 m/s.

In summer, for actual wind speed less than 30 m/s, all three deviation parameters are found to decrease markedly with increasing actual wind speed. A slight decrease of these parameters appears when mean wind speed is over 30 m/s.

Figure 5 also shows that the mean values of these parameters for wind speeds less than 20 m/s are larger in summer than in winter. But for wind speeds greater than 20 m/s, the parameters have essentially the same mean value summer and winter. We note that mean relative vector wind deviation, $\overline{R}_v$, has values of less than 40 percent when wind speed is greater than 20 m/s. A similar feature also shows in the results of a study by Neiburger and Angell (1956) using constant-pressure balloon trajectory data at the 300-mb level. Therefore, the use of the geostrophic wind approximation in the free atmosphere between the 500- and 100-mb level should probably be restricted to wind speeds greater than 20 m/s to keep the vector wind errors under 40 percent. The angle between actual wind and geostrophic wind directions is found to be small (10° to 15°) for wind speeds greater than 20 m/s.

4. ERRORS AND TRUE GEOSTROPHIC DEVIATION

In this section, errors in the computation of geostrophic deviations that arise from two major factors—inaccurate pressure-height and rawin observations—are examined. True geostrophic deviations and total wind accelerations are estimated taking these errors into consideration.

TABLE 1.—*Root-mean-square vector wind errors* (m/s) *in* (A) *the computation of geostrophic wind* (*caused by pressure-height errors*) *and* (B) *rawin measurement*

Pressure (mb)		500	400	300	250	200	150	100	70	50	30	20
A		2.5	3.7	5.0	5.7	7.0	7.9	9.3	9.9	10.6	10.9	11.6
B	Winter	0.7	1.4	2.1	2.5	3.1	2.7	2.1	1.6	2.0	2.8	3.1
	Summer	0.7	0.9	1.2	1.3	1.6	1.6	1.7	1.8	1.5	1.1	0.9

TABLE 2.—*Overall inherent root-mean-square vector wind errors* (m/s) *in the computation of geostrophic wind deviation and apparent root-mean-square vector wind deviation*

	Pressure (mb)	500	400	300	250	200	150	100	70	50	30	20
Winter	Errors	2.6	4.0	5.4	6.2	7.7	8.4	9.5	10.0	10.0	11.3	12.7
	Deviations	8.1	9.3	12.4	13.8	14.7	13.8	10.3	11.1	12.6	14.8	17.1
Summer	Errors	2.6	3.7	5.1	5.8	7.2	8.1	9.4	10.1	10.7	11.0	11.2
	Deviations	5.5	6.3	8.4	9.3	10.4	10.3	10.6	13.2	13.3	16.7	14.9

The computation of geostrophic wind is, of course, subject to errors in the determination of pressure-height. These errors are largely produced during the computation of each individual pressure-height sounding by errors in measuring temperatures and pressures. According to Murray (1954), if the geostrophic wind at the center of a square of side L is derived from four radiosonde observations at the corners of the square, then the rms vector error in geostrophic wind is $\sqrt{2}\,g\,E_h/fL$ where g is the acceleration of gravity, f is the Coriolis parameter and E_h is the rms error of pressure-height observation. In this study, L is taken to be 540 km, which is the average distance between the four corner radiosonde stations. The rms errors in pressure-heights, E_h, computed from the AN/GMD–1 radiosonde observations were estimated by Lenhard (1970). His results are used in this study. With g and f set equal to 9.8 $\mathrm{m \cdot s^{-2}}$ and 7.29×10^{-5} $\mathrm{s^{-1}}$, the estimated rms vector errors of geostrophic wind caused by pressure-height errors were computed by Murray's formula and are shown in table 1.

Ference (1951) discussed the errors in GMD–1 wind measurement and used two wind cross-sections observed at Belmar, N.J., during December and July to compute the rms vector errors. The estimated wind measurement errors also given in table 1 were obtained according to his results. We see that, despite the improvement in the accuracy of pressure-height data, the errors in pressure-height observations still make the largest contribution to the errors in the computation of geostrophic deviations.

The apparent deviation is considered to be due to the combined effect of the true deviations and the errors in the computation of these deviations. On the assumption that these errors are independent, the errors caused by inaccurate pressure-height and wind measurements can thus be combined to yield the overall errors inherent in the method employed in this study. These overall errors were obtained from the numerical values in table 1 by the standard analysis of variance technique and are shown in table 2. The rms apparent vector wind deviations are also listed in the table for comparison with the errors. In general, errors caused by erroneous wind measurements and pressure-height computation account for a large portion of the apparent deviation at higher levels (above the 150-mb level) whereas they account for only a relatively small fraction of the apparent deviation at lower levels.

If the errors are assumed to be normally distributed about zero, then the mean absolute vector wind errors caused by inaccurate pressure-height and wind observations will be about 0.8 of the overall rms errors.[1] We note that, due solely to the errors inherent in the method employed in this study, a comparison of actual and geostrophic winds would show a mean absolute vector wind deviation with values equal to 80 percent of the values of the errors shown in table 2 at specified levels and seasons even if the actual winds were in perfect balance with the pressure field.

With the magnitude of these errors estimated, an attempt was made to estimate the true deviation. This was done by considering that the mean square of the apparent vector wind deviation, $[\mathrm{rms}\,(v)]^2$, is a sum of the mean square of true vector wind deviation and the

[1] A property of the normal distribution which can be shown by evaluating

$$\int_{-\infty}^{\infty} |x| N(x; 0, \sigma) dx,$$

where $N(x; 0, \sigma)$ is the normal distribution function of variable x with mean equal to 0 and standard deviation σ.

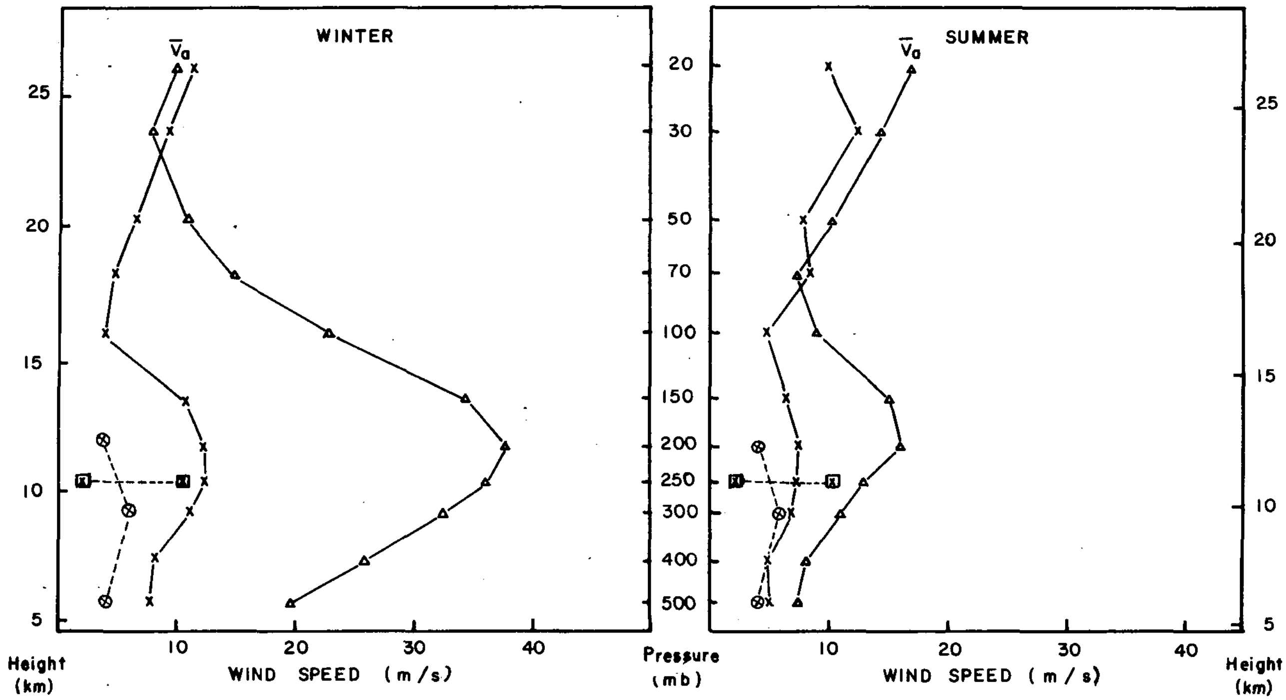

FIGURE 6.—True root-mean-square (rms) geostrophic vector wind deviation (x) and mean actual wind speed $\overline{V}_a$. Symbols ⊗ and ⊠ denote rms values of geostrophic vector wind deviation obtained by Murray (1954) and Endlich and McLean (1960), respectively.

TABLE 3.—*Mean total wind acceleration (in units of 10^{-4}* m·s^{-2})

Pressure (mb)	500	400	300	250	200	150	100	70	50	30	20
Winter	3.4	3.2	4.4	4.6	5.0	3.6	1.1	1.2	2.3	2.8	3.4
Summer	2.0	1.8	2.3	2.6	2.5	2.0	1.3	2.5	2.3	4.2	3.5

mean square of the errors in computation; that is,

$$[\text{rms (apparent deviation)}]^2 = [\text{rms (true deviation)}]^2 + [\text{rms (errors)}]^2.$$

The estimated true vector wind deviations computed by the relation above are plotted in figure 6 along with the mean actual wind speed, $\overline{V}_a$.

It is found in figure 6 that between the 500- and the 100-mb levels for both winter and summer the true deviation varies directly with the mean actual wind speed. Above the 100-mb level an inverse relationship shows in winter, but in summer a direct relationship is reestablished between 50 and 30 mb. The estimated values for the month of April obtained by Murray (1954) were plotted in the same figure. These values are in agreement with the estimates for summer in this study. The true geostrophic speed deviations were estimated to have rms values of 10.3 m/s for cyclonic flow and 2.1 m/s for straight flow at jet stream levels by Endlich and McLean (1960) (also shown in fig. 6). These values are fairly close to the values obtained in this study, considering that rms vector wind deviation is some 3 m/s larger than rms speed deviation at jet stream levels (see fig. 3).

The magnitude of the total wind acceleration can be shown to be equal to the product of the Coriolis parameter and the absolute geostrophic vector wind deviation (e.g. Haltiner and Martin 1957). The mean true absolute vector wind deviations were obtained in this study as the absolute values of the difference between the mean apparent absolute vector wind deviations and the mean absolute vector wind errors (80 percent of the values of errors listed in table 2). The accelerations thus computed (see table 3) range from about 1×10^{-4} m·s^{-2} to as large as 5×10^{-4} m·s^{-2}. Godson (1950) has found that at 10,000 ft the total mean wind acceleration was about 40 mi·hr^{-1}·day^{-1} (2.1×10^{-4} m·s^{-2}). Mean total wind acceleration at 300 mb calculated from constant-pressure balloon trajectory data (Neiburger and Angell 1956) was 7.67×10^{-4} m·s^{-2}.

5. CONCLUSIONS

An attempt to compute the apparent geostrophic deviation and to estimate the true geostrophic deviation in a broad layer from the 500-mb level to the 20-mb level above the El Paso–White Sands Missile Range area has been made.

Analysis of the apparent geostrophic deviation reveals (for levels below 100 mb) that:

1. Both the absolute geostrophic vector wind deviation and the absolute geostrophic speed deviation tend to increase with increasing actual wind speed.

2. Both the relative geostrophic vector wind deviation and the relative geostrophic speed deviation decrease with increasing wind speed when wind speed is less than 40 m/s and become nearly constant otherwise.

3. For wind speed less than 40 m/s, the geostrophic direction deviation is inversely proportional to the wind speed. For wind speed greater than 20 m/s, the angle between geostrophic and actual wind direction on the average for the entire layer (from 500 to 100 mb) is small (less than 15°).

4. To keep relative vector wind errors under 40 percent, the use of the geostrophic approximation probably should be restricted to wind speeds greater than 20 m/s.

The analysis of errors and the estimation of the true geostrophic deviation lead to the following conclusions:

1. Despite the improvement in radiosonde accuracies, errors in the computation of geostrophic wind deviation using rawin and pressure-height data still become serious at higher levels. Errors in pressure-height data at all levels make the largest contribution to the overall errors in the computation of the geostrophic wind deviations.

2. The true absolute geostrophic vector wind deviations tend to increase with increasing mean wind speed. This true deviation, in terms of its rms values, has a maximum of 12.5 and 7.5 m/s at the 200-mb level for winter and summer, respectively.

3. Estimation of the total mean wind acceleration yielded values of the order of 1×10^{-4} to 5×10^{-4} $m \cdot s^{-2}$ at various levels and seasons.

ACKNOWLEDGMENTS

The research reported in this paper has been supported by White Sands Missile Range under the terms of Contract No. DA-29-040-AMC-1802(E). Computation time on the Control Data Corp. 6600 computer was provided by The University of Texas Computation Center.

REFERENCES

Bannon, John Kerman, "The Angular Deviation of the Wind From the Isobars at Liverpool," *Quarterly Journal of the Royal Meteorological Society*, Vol. 75, No. 324, London, England, Apr. **1949**, pp. 131–146.

Endlich, Roy M., "Direct Computation of Geostrophic Winds From Observed Winds Using the Balance Equation," *Journal of Applied Meteorology*, Vol. 7, No. 6, Dec. **1968**, pp. 994–1003.

Endlich, Roy M., and McLean, G. S., "Geostrophic and Gradient Departures in Jet Streams," *Journal of Meteorology*, Vol. 17, No. 2, Apr. **1960**, pp. 135–147.

Ference, Michael, Jr., "Instruments and Techniques for Meteorological Measurements," *Compendium of Meteorology*, American Meteorological Society, Boston, Mass., **1951**, 1334 pp. (see pp. 1207–1222).

Giles, Keith G., and Peterson, Roy E., "A Study of Wind Velocities Measured From Constant-Pressure Balloons," *Journal of Meteorology*, Vol. 14, No. 6, Dec. **1957**, pp. 569–572.

Godson, Warren Lehman, "A Study of the Deviations of Wind Speeds and Directions From Geostrophic Values," *Quarterly Journal of the Royal Meteorological Society*, Vol. 76, No. 327, London, England, Jan. **1950**, pp. 3–15.

Haltiner, George J., and Martin, Frank L., *Dynamical and Physical Meteorology*, McGraw-Hill Book Co., Inc., New York, N.Y., **1957**, 470 pp. (see chapter 12, pp. 178–199).

Houghton, Henry G., and Austin, James M., "A Study of Non-Geostrophic Flow With Applications to the Mechanism of Pressure Change," *Journal of Meteorology*, Vol. 3, No. 3, Sept. **1946**, pp. 57–77.

Kays, Marvin D., "A Note on the Comparison of Rocket and Estimated Geostrophic Winds at the 10-Mb Level," *Journal of Applied Meteorology*, Vol. 5, No. 1, Feb. **1966**, pp. 129–131.

Kochanski, Adam, "Ageostrophic Deviations and Wind Prognoses," *Journal of Meteorology*, Vol. 15, No. 1, Feb. **1958**, pp. 84–90.

Lenhard, Robert W., "Accuracy of Radiosonde Temperature and Pressure-Height Determination," *Bulletin of the American Meteorological Society*, Vol. 51, No. 9, Sept. **1970**, pp. 842–846.

Murray, R., "On the Accuracy of Contour Charts in Forecasting Upper Winds," *Professional Notes*, Vol. 7, No. 110, Meteorological Office, London, England, **1954**, 11 pp.

Murray, R., and Daniels, Sylvia M., "Transverse Flow at Entrance and Exit to Jet Streams," *Quarterly Journal of the Royal Meteorological Society*, Vol. 79, No. 340, London, England, Apr. **1953**, pp. 236–242.

Neiburger, Morris, and Angell, James K., "Meteorological Applications of Constant-Pressure Balloon Trajectories," *Journal of Meteorology*, Vol. 13, No. 2, Apr. **1956**, pp. 166–194.

Neiburger, Morris, Sherman, Leon, Kellogg, William Welch, and Gustafson, A. F., "On the Computation of Wind From Pressure Data," *Journal of Meteorology*, Vol. 5, No. 3, June **1948**, pp. 87–92.

Wu, Hsing-Wu., "Geostrophic Wind Deviation in the Upper Troposphere and Lower Stratosphere in the El Paso-White Sands Area," *Report* No. 26, Atmospheric Science Group, College of Engineering, University of Texas at Austin, Dec. **1970**, 54 pp.

Zobel, R. F., "The Evaluation of Winds at 200 Millibars From Contour Charts," *Meteorological Magazine*, Vol. 87, No. 1028, London, England, Feb. **1958**, pp. 44–49.

[*Received March 22, 1971; revised August 3, 1971*]